

ROBONAUT 2 - PREPARING FOR INTRA-VEHICULAR MOBILITY ON THE INTERNATIONAL SPACE STATION

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Robonaut 2 (R2) has been undergoing experimental trials on board the International Space Station (ISS) for more than a year. This upper-body anthropomorphic robotic system shown in Figure 1 has been making steady progress after completing its initial checkout. R2 demonstrated free space motion, physically interacted with its human crew mates, manipulated interfaces on its task board and has even used its first tool. This steady growth in capability will lead R2 to its next watershed milestone. Developers are currently testing prototype robotic climbing appendages and a battery backpack in preparation of sending flight versions of both subsystems to the ISS in late 2013. Upon integration of its new components, R2 will be able to go mobile inside the space station with a twofold agenda. First, R2 will learn to maneuver in microgravity in the best possible laboratory for such a task. Second, it will start providing early payback to the ISS program by helping with intra-vehicular (IVA) maintenance tasks. The experience gained inside the ISS will be invaluable in reducing risk when R2 moves to its next stage and is deployed as an extra-vehicular (EVA) tool.

Even on its current fixed base stanchion, R2 has already shown its capability of performing several maintenance tasks on the ISS. It has measured the air flow through one of the stations vents and provided previously unavailable real time flow data to ground operators. R2 has cleaned its first handrail, exciting some crew members that perhaps Saturday morning housekeeping on the station may someday become a task they can hand off to their robotic colleague. Other tasks, including using radio frequency identification (RFID) tools for inventory tasks or vacuuming air filters, have also been suggested and will be explored. Once mobile, R2 will take on these tasks and more to free up crew time for more important science and exploration pursuits. In addition to task exploration, research and testing is happening on orbit to prepare for R2 mobility operations. The current vision system in R2's head is being used to identify and localize IVA handrails throughout the US Lab and ground control software is being updated and integrated in advance of supporting mobility operations.

R2 in its mobile configuration has significant capability for moving from one location to another. Figure 2 shows a prototype version of the future on-orbit system in the reduced gravity facility, ARGOS. Each appendage, or leg, features seven degrees of freedom as well as a multi-use gripping end effector. Each of the fourteen degrees of freedom are single-axis series elastic actuators. The overall length of the robot was designed to be long enough to safely traverse ISS nodes while still allowing R2 to maneuver within the size constraints of the lab. The end effectors will have a sensor

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Figure 1: Robonaut 2 interfacing with its taskboard

package that includes cameras, load cells, and position sensors. The end effector will be capable of attaching to handrails and seat track inside the ISS, and the sensor package will be instrumental in automating safe grapple operations.

R2 will feature embedded joint-level impedance control. The coordinated Cartesian position and force controller consists of an inverse kinematics calculation that will generate joint position commands as well as dynamics algorithms that compensate for the robot's inertia through feed-forward torques and joint position loop gains while it moves through the ISS. The controller will also limit the torque that each joint can apply, much as the current upper body does, to ensure safety as crew members interface with and work around R2. The control algorithm will intrinsically limit the Cartesian velocity and acceleration of the end effectors, but these values as well as force and torque values will be constantly monitored as an additional safety check. Overall, this control algorithm provides exceptional performance and repeatability while maintaining strict safety constraints.

The operational strategy for climbing around the ISS will include both supervisory inputs from ground-based operators as well as autonomous capabilities of the robot. R2 will be given a model of the ISS and an operational plan, or sets of tasks, that it needs to complete. A combination of robotic machine vision and operator inputs will determine the obstacle field to avoid during its traverse. Sample based path planning methods are being explored to allow the robot to autonomously generate motion plans based on the environment and the robot's capabilities. These plans will be verified by operators and then executed under ground supervision. R2 will use longer range vision sensors in its head to find handrail locations to feed to the sample based path planner, and then will use the 3D vision sensor package in the leg end effectors to precisely drive the end effector towards its specified grasp point. Along its path and while connected to the ISS, null space optimizations will allow R2 to avoid self-collisions, joint limits or singularities, and to limit the forces applied to the station.

The next phase of Robonaut 2 as an IVA mobile system will provide extraordinarily valuable



Figure 2: R2 testing mobility algorithms in ARGOS

microgravity operational experience. Control strategies will be honed prior to EVA operations in the closest analog to that environment while utilizing all the readily available resources for engineering development that exist inside the ISS. Having a mobile robotic helper inside the ISS will result in time savings for the crew as R2 finds suitable housekeeping and maintenance tasks to perform. Finally, the time spent working inside the ISS laboratory will result in well tested and reliable semi-autonomous and autonomous locomotion capabilities that will position R2 for success when it performs its first EVA tasks.